Forward Silicon Vertex Tracker for the PHENIX experiment at RHIC

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Abstract. The PHENIX experiment at RHIC is well in the process of constructing a silicon vertex tracker consisting of a central barrel component (already undergoing commissioning), as well as two forward rapidity components. This report gives an overview of the physics goals of the forward vertex tracker (FVTX), and gives the current status of its construction. It is scheduled to be completed this year and commissioned during the next RHIC run.

1. Introduction

The main goal of the RHIC heavy ion program is the discovery of the novel ultra-hot high-density state of matter predicted by the fundamental theory of strong interactions and created in collisions of heavy nuclei, the Quark-Gluon Plasma (QGP). From measurements of the large elliptic flow of light mesons and baryons and their large suppression at high transverse momentum p_T that have been made at RHIC, there is evidence that new degrees of freedom, characteristic of a strongly-coupled deconfined QCD medium, drive the dynamics of nucleus-nucleus collisions. It has been recognized, however, that the potential of light quarks and gluons to characterize the properties of the QGP medium is limited and the next phase of the RHIC program calls for the precise determination of its density, temperature, opacity and viscosity using qualitatively new probes, such as heavy quarks.

We are in the construction phase of two Forward Silicon Vertex Trackers (FVTX) for the PHENIX experiment that will directly identify and distinguish charm and beauty decays within the acceptance of the muon spectrometers. The FVTX will provide this essential coverage over a range of forward and backward rapidities ($1.2 < |y| < 2.4$) – a rapidity range coverage which not only brings significantly larger acceptance to PHENIX but which is critical for separating cold nuclear matter effects from QGP effects and is critical for measuring the proton spin contributions over a significant fraction of the kinematic range of interest. In addition, the FVTX will provide greatly reduced background and improved mass resolution for di-muon events, culminating in the first measurements of the ψ' and Drell-Yan at RHIC. These same heavy flavor and di-muon measurements in p+p collisions will allow us to place significant constraints on the gluon and sea quark contributions to the proton's spin and to make fundamentally new tests of the Sivers function universality.

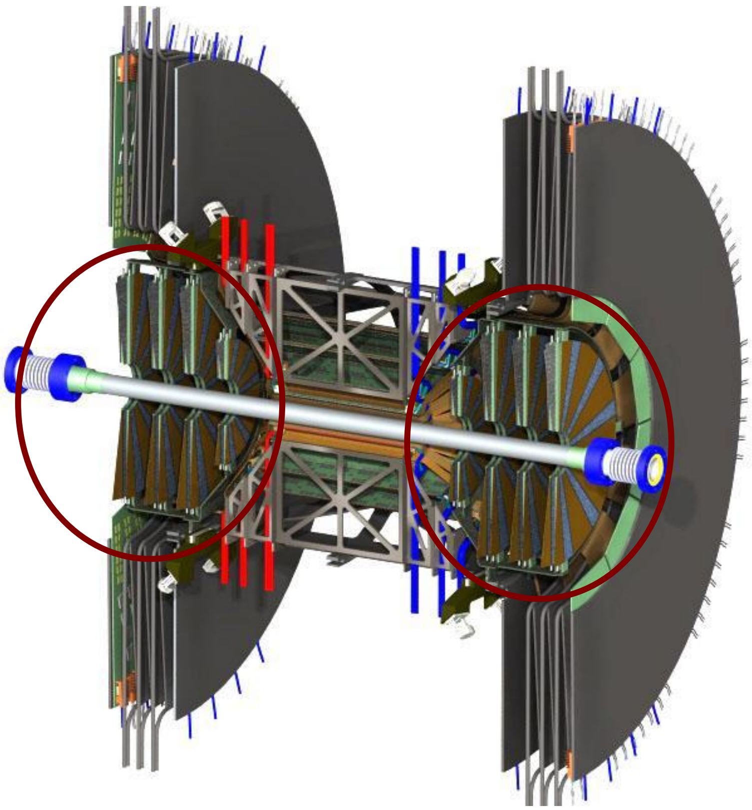

Figure 1 Half-layout of the PHENIX FVTX showing the four vertical planes of each end cap in the red circles.

The FVTX detectors will extend the vertex capabilities of the PHENIX Silicon Vertex Tracker (VTX) to cover a much larger rapidity interval, including forward and backward rapidities, and allow displaced track and secondary vertex measurements in conjunction with the PHENIX muon arms. The heavy flavor measurements provided by these detectors will move us from making qualitative statements that heavy flavor is suppressed in heavy ion collisions to being able to distinguish among models which include radiative energy loss, collisional energy loss, and/or collisional dissociation for light and heavy quarks—a distinction which is not possible without the addition of a vertex detector, and without which there remains large uncertainty in what the various suppression mechanisms are for light and heavy quarks and what the extracted properties of the medium should be. By adding vertexing capability covering the muon arms we not only increase the acceptance for physics observables by a factor of 3-10 but also allow coverage in the forward rapidity regions – coverage which is critical to separate cold nuclear matter effects from QGP effects, and critical for understanding the geometric extent of the medium.

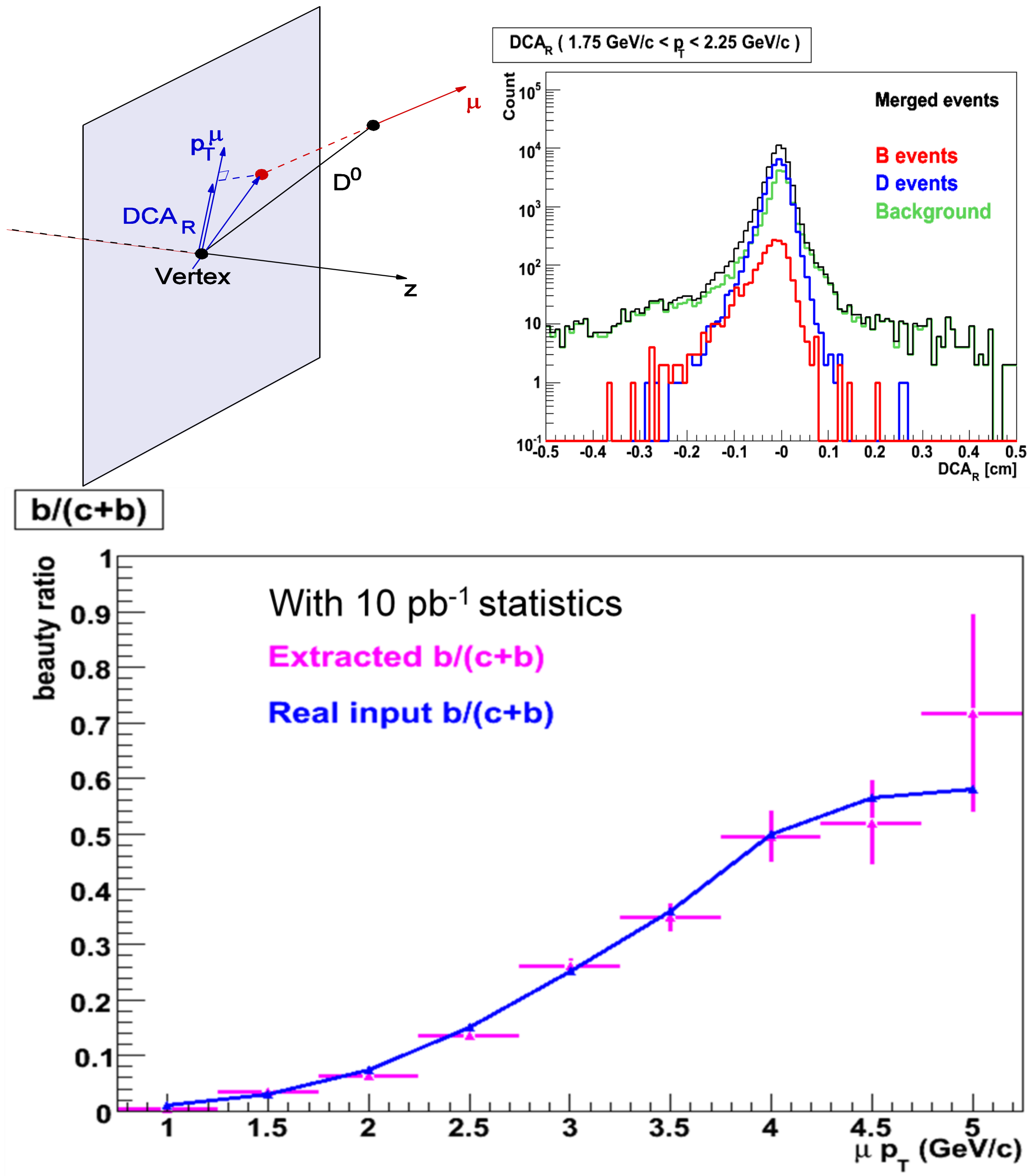

Figure 2. Upper left panel: Definition of the Radial Distance of Closest Aproach (DCA_R). Upper right panel: DCA_R for simulated charm, beauty and background (light meson decay) events. Bottom panel: Extracted beauty/total heavy meson ratio from a fit to the DCA_R distributions, compared to the simulated input ratio.

J/ψ vector mesons are also considered to be a very sensitive probe of the dense matter created in heavy ion collisions and have been shown to be highly suppressed at RHIC. At SPS the suppression of J/ψ production was one of the measurements given to support the statement that a new state of matter (the QGP) was formed, so the RHIC J/ψ results have been highly anticipated and are of great interest to the heavy-ion community. The baseline PHENIX detector was designed to provide good measurements of inclusive J/ψ production; however, to quantitatively understand the modification of J/ψ production in the medium, these measurements must be coupled with precise open heavy flavor measurements that can be used with recombination models to determine the contribution to J/ψ production that comes from random c and cbar pairs combining to form J/ψs as opposed to prompt J/ψ production. Since J/ψs produced by recombination have different kinematic distributions from prompt J/ψ production, and will *enhance* J/ψ production rather than suppress the production, the recombination contributions must be understood to extract the amount of medium-induced suppression. The FVTX will provide the needed precision open heavy flavor measurements to allow for a much better understanding of J/ψ production via recombination. Together with this, we need to measure production of other vector mesons such as ψ' and χ_c to understand Debye screening contributions. The different vector mesons have different screening radii, so measuring the difference in their suppression patterns allows one to infer the radius at which Debye screening becomes significant. Additionally, the ψ' and χ_c contribute to J/ψ production via feed-down, so measuring their suppression pattern allows one to understand how much of the J/ψ suppression is inherited from ψ', χ_c suppression and how much is suppression of prompt J/ψ production. With the addition of the FVTX detector, we will be able to separate the ψ' and J/ψ production through improved mass resolution and enhanced background rejection. These new measurements, coupled with the J/ψ measurements should significantly advance our understanding of J/ψ suppression in heavy ion collisions.

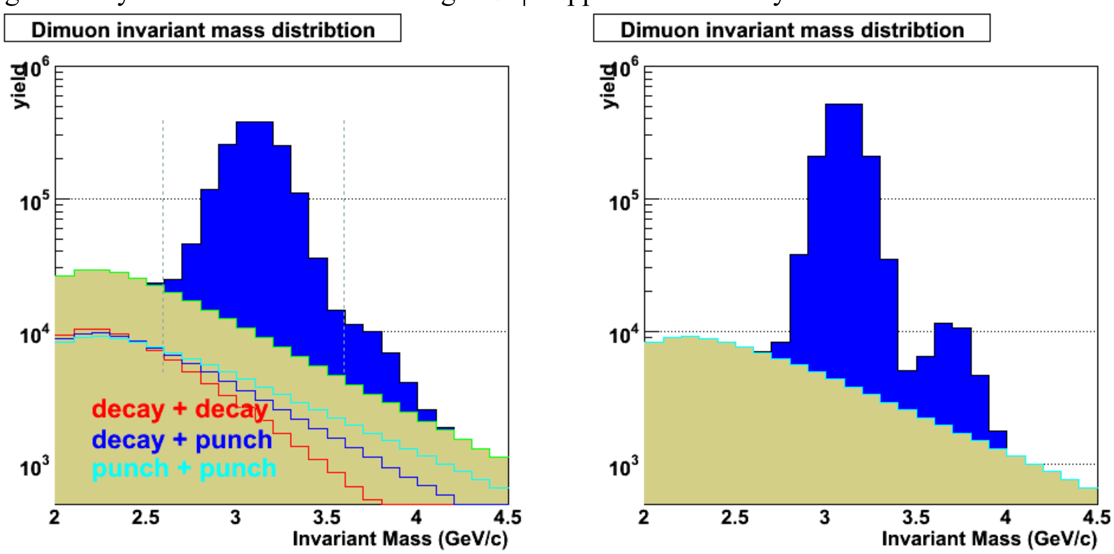

Figure 3. Di-muon invariant mass spectrum in simulated 200GeV p+p collisions without (left panel) and with (right panel) the use of the FVTX detector's tracking before the magnet steel, demonstrating the improvement in the muon momentum resolution and the reduction in backgrounds.

The RHIC spin program was developed to determine the gluon and sea quark contributions to the proton's spin and (possibly) put constraints on the angular momentum contributions to the spin. With the addition of the FVTX detectors, we will significantly extend the x coverage for gluon spin measurements in PHENIX by adding precision heavy flavor asymmetry measurements at forward and backward rapidities which are sensitive to the gluon spin distribution. These measurements cannot be made with the baseline detector alone. Measuring the gluon spin distributions over a large x coverage is critical for extracting $\Delta G = \int \Delta G(x)dx$. The FVTX detector will provide precise Drell-Yan measurements (in conjunction with the muon arms), which will allow measurements of sea quark contributions to the proton's spin because the Drell-Yan production asymmetry is sensitive to the ubar polarization. This provides us a unique opportunity to produce a sea quark measurement which is complimentary to the W measurements that are proposed. The FVTX will also provide unique track reconstruction constraints which will help reject hadronic backgrounds which contribute to the single muon spectra. The single muon spectra will be used to measure sea quark contributions to the proton spin by extracting the $W \rightarrow \mu X$ single spin asymmetry at high p_T so background rejection at high p_T is essential to making a precision measurement.

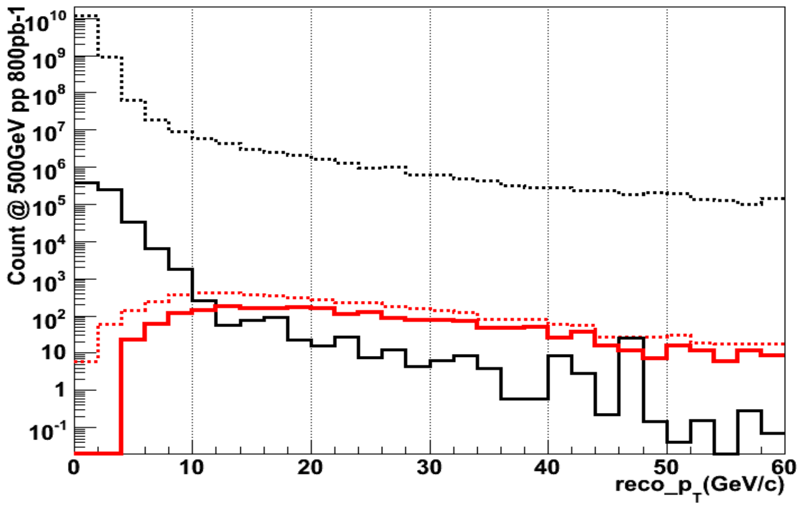

Figure 4. Background (black lines) and W signal (red lines) without FVTX (dotted lines) and with FVTX (solid lines).

The Drell-Yan measurements with polarized proton beams will also allow for a new fundamental test of QCD theory. Sivers-type single-spin asymmetry has been observed in semi-inclusive DIS at HERMES and COMPASS very recently. A fundamental prediction of QCD is that such effects will give an opposite sign in the transverse single spin asymmetry in DY production in p+p collisions. Its verification (or not) will be an important milestone in our study of the strong interaction, as it tests all concepts for analyzing hard-scattering reactions that we know of today.

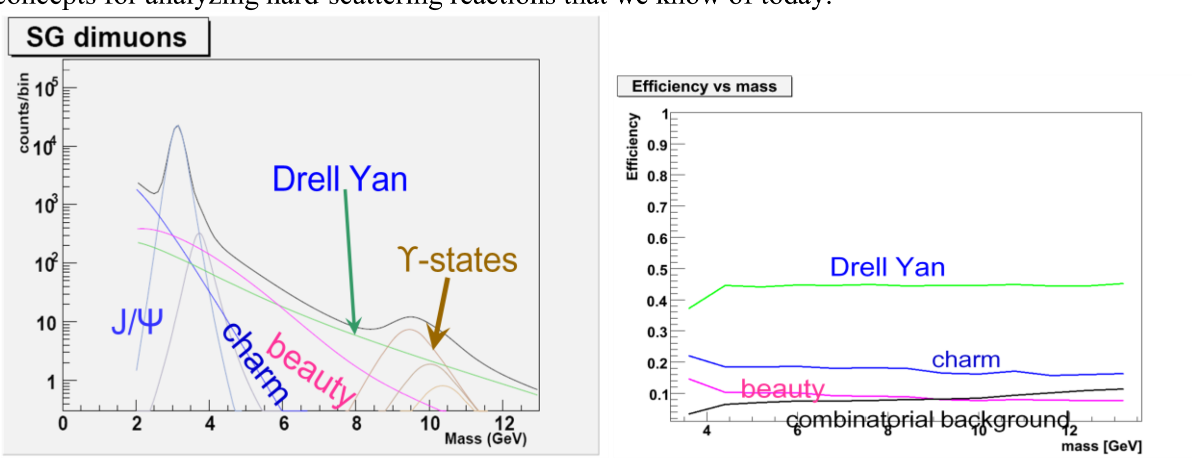

Figure 5. Left panel: Di-muon invariant mass "cocktail plot" before imposing FVTX cuts. Right panel: Enhancement of the Drell Yan signal over background in the 4 -12 GeV mass range using FVTX cuts.

The FVTX detectors, covering forward and backward rapidities ($1.2 < |y| < 2.4$) are ideally suited to study the fundamental QCD interactions in d+A collisions at RHIC. Light hadron results indicate that the suppression pattern observed at forward rapidity is suggestive of nuclear shadowing or saturation physics at small values of Bjorken-x. It has been found, however, that such attenuation is not consistent with the measured shadowing in the nuclear structure functions in DIS. Preliminary measurements have instigated recent theoretical activity which suggests that the physics of d+A collisions is much more complex. Nuclear effects that potentially play a role are the Cronin effect, cold nuclear matter energy loss (stopping power of large nuclei) and dynamical shadowing from coherent multiple scattering. The FVTX upgrades will help open new physics channels for precision measurements, such as the Drell-Yan process, where initial- and final state-effects can be separately investigated.

In addition, the FVTX detectors will provide moderate rapidity gap correlation measurements (when combined with the midrapidity PHENIX detectors) and large rapidity gap (when the forward and backward FVTX are used) for studying di-jet correlations. It has been argued in the framework of CGC phenomenology that the dominant particle production mechanism in d+A reactions is 2-to-1 processes, such as gluon fusion and quark scattering on a background gluon field. In contrast, the lowest order process in collinear factorized pQCD is 2-to-2 scattering which would produce a clear di-jet signal. Therefore, to validate or disprove theoretical models of jet production in d+A collisions jet-jet correlation measurements, including heavy quark triggered jets, are of critical importance.

With the present PHENIX detector, heavy-quark production in the forward and backward directions has been measured indirectly via the observation of single muons. The current measurements are inherently limited in accuracy by systematic uncertainties resulting from the large contributions to the single muon spectra from prompt pion and kaon semi-leptonic decays and from pion and kaons which punch through the entire muon system and are mistakenly tagged as muons. In addition, the analysis does not allow for a model-independent separation of the charm and bottom contributions. The FVTX detector will provide vertex tracking with a distance of closest approach (DCA) resolution in r-z that is better than 100 μm over a large coverage in rapidity ($1.2 < |\eta| < 2.2$) and with full azimuthal coverage. This will allow for vertex cuts which separate prompt particles from decay particles and short-lived heavy quark mesons from long-lived light mesons (pions and kaons). In addition, bottom measurements can be made directly via $B \rightarrow J/\psi + X$ by looking for a displaced J/ψ vertex, and this will allow charm and bottom contributions to be separated in semi-inclusive single lepton measurements. Therefore, with this device fundamentally new measurements can be made and current muon measurements will be significantly enhanced.

The precision of the J/ψ and other dimuon measurements in AuAu collisions is currently limited by the large amount of combinatorial background that must be subtracted from the opposite sign dimuon signal obtained with the muon tracker and by the inherent mass resolution. With added rejection power for pion and kaon decays, the significance of all dimuon measurements will be greatly improved. Further improvement in these measurements results from the improved mass resolution, which will be attained because of the more accurate determination of the opening angles of the dimuons. All together, this will result in improved dimuon data as well as provide access to several new measurements: separation of ψ' from J/ψ, extraction of a Drell-Yan signal from the dimuon continuum, extraction of $B \rightarrow J/\psi$ and measurement of upsilons at central rapidity.

2. Technical description and status of the detector

The FVTX will be composed of two endcaps, with four silicon mini-strip planes each, covering angles ($1.2 < |\eta| < 2.2$) that match the two muon arms. Each silicon plane consists of wedges of mini-strips with 75 μm pitch in the radial direction and 3.75° wide strips in phi, which translates to lengths in the phi direction varying from 2.8 mm at small angles to 12.1 mm at 35 degrees. An r-z DCA resolution of 100 μm can be achieved with a maximum occupancy per strip in central Au+Au collisions of less than 2.8%. In Figure 1, the four stations of the North and South FVTX arms are circled in red, the central support structure for the VTX system can be seen between the two, and the large gray planes surrounding the FVTX sensors are the planes that will hold the readout electronics for the VTX and FVTX systems. A picture of one half-cage of the detector is shown in Figure 6.

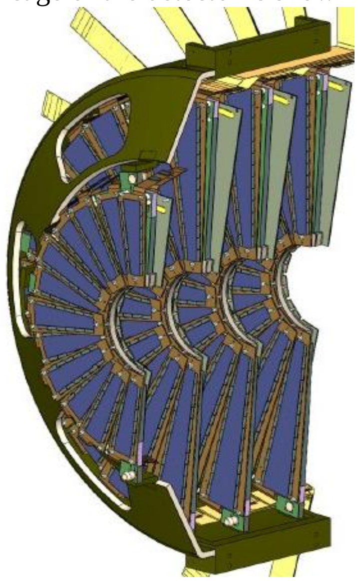

Figure 6. One half-cage containing the four half-disks of sensor wedges. Each wedge is overlapped sufficiently to give full azimuth coverage.

The FVTX will consist of approximately 1.1 million mini-strips that will be read out with an IC chip (FPHX) designed by Fermilab, which is wire-bonded directly to the mini-strips. This chip provides analog and digital processing with zero-suppression and produces a digital output which is "data-pushed" at 200 Mbps to intelligent readout boards containing FPGAs. The data are then transformed into the standard PHENIX format and transmitted to the PHENIX DAQ system via fiber optics.

We are using standard p-on-n silicon strip technology, which has been the baseline detector technology for dozens of silicon trackers in nuclear and high-energy physics experiments. In a p-on-n detector, the output signal is generated by the collection of positive charge carriers. The FPHX chip is compatible with positive charge collection. The FPHX is also designed to have leakage current compensation at the front-end, up to 100 nA/ strip. This compensation circuitry allows the possibility of reading out sensors with dc output connections to the FPHX chip, however our sensors are ac-coupled.

The strips are ac-coupled directly on the sensor. The capacitor is made by depositing an oxide layer of approximately 200 nm on top of, and over the entire length of the p-implant. An aluminum metallization is placed on top of the oxide to complete the capacitor and to form the readout conductor. The bias connection to the p-implants is made by a polysilicon resistor of approximately 1.5 MΩ, which is electrically connected to a common bias ring on one end, and to the p-implant on the other end. There is an individual polysilicon resistor for each strip, and three sets of pads on each strip: a spy pad which penetrates the oxide layer to allow probing of the dc characteristics of the strip; probe pads, which are dedicated for probing the ac characteristics of the strips; and bond pads which are only used to wire bond from the detector to the electronics (see Figure 7). All non-metal surfaces of the top side of the sensor are covered with a passivation of silicon-oxide or silicon-nitride. A guard ring is implanted around the perimeter of the wedge between the bias ring and the cut-edge of the sensor to prevent breakdown at the cut-edge of the sensor under a normal range of bias voltage. The sensor breakdown voltage is specified to be ≥200V or ≥50V above operating voltage, whichever is greater. There is no need to specify higher breakdown voltage, or to incorporate multiple guard ring structures, because an integrated 10 year radiation dose of 200 krads does not require it. Leakage current at 20˚ C is specified to be $\leq$ 160 nA/cm^2 at operating voltage. All of these processes and specifications are standard in the industry.

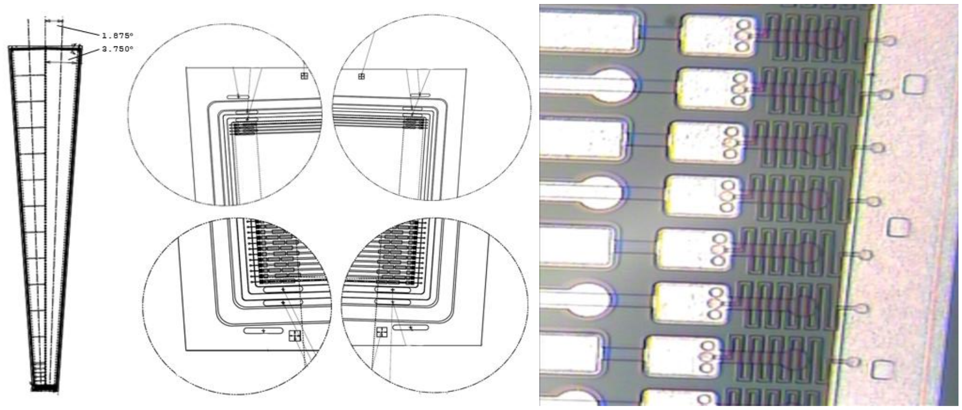

Figure 7. Left panel: Schematic drawing of the silicon sensors with two rows of strips oriented perpendicular to the radial. Right panel: Close-up view of strips connected to AC-coupled pads, then DC-coupled test pads, the through a poly-silicon resistor to the bias ring (from left to right).

The sensor readout strips will operate at ground potential, and a positive bias voltage will be applied to the backside of the sensor to fully deplete the sensor volume for efficient charge collection. The large sensor wedge for disks 2, 3, and 4 is approximately 126.5 mm high, 8.7 mm wide at the inner radius, and 25.3 mm wide at the outer radius. The small sensor wedge for disk 1 is approximately 59.5 mm high, 8.7 mm at the inner radius, and 16.5 mm at the outer radius. Our production sensors were produced by Hamamatsu with very good results. Hamamatsu tested and reported leakage current for each strip, and we verified these values on a fraction of the delivered sensors.

The sensor wedge consists of a stack up of a carbon support backing, kapton High-Density Interface (HDI), and sensor and chips. The carbon backing serves as a carrier on which the sensor, HDI, and chips can be mounted separately from the cooling plate. This modular arrangement allows us to fabricate and test all of the wedges separately.The HDI is a seven layer polyamide flexible printed circuit consisting of a bias layer, two signal layers, one ground layer, two power layers, and a component layer. All control lines (which are not active during data taking) are routed under the sensor and all output lines are routed towards the edge of the wedge thus insuring that the output lines will not couple into the signal lines on the sensor. The number of lines required (8 pairs for the control lines and 2 signal pairs per chip for the output lines) fit into the width of the HDI and the line pitch of the HDI challenging, but technically achievable with conventional polyamide manufacturing techniques. Pictures of the unassembled and assembled HDI and wedges are shown in Figure 8.

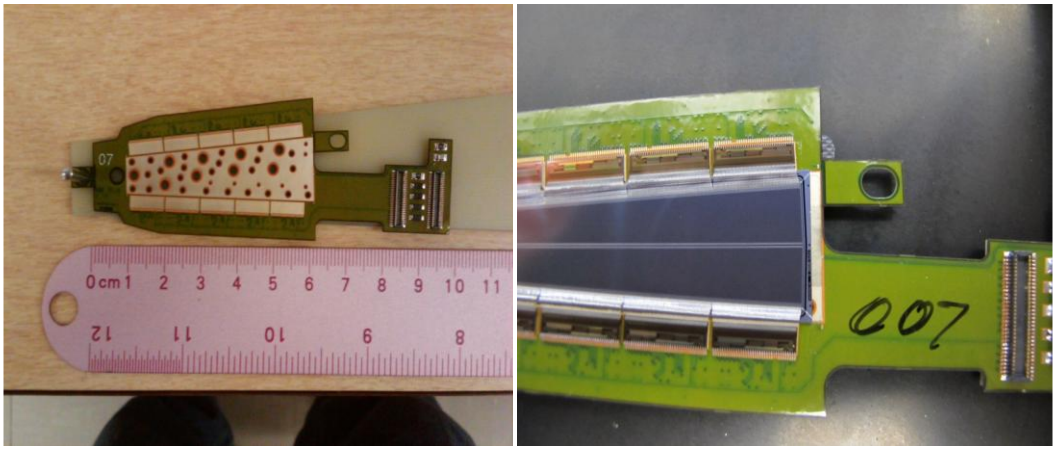

Figure 8. Left panel: A unassembled production station 1 High-Density Interconnect card (HDI). The central region has the sensor bias plane, with ground planes surrounding it for the placement of the FPHX read-out chips. Right panel: An assembled wedge with the sensor, FPHX chips and wire bonds all in place.

The FPHX is a custom IC designed by engineers in the Fermi National Accelerator Laboratory Particle Physics Division. The chip design borrows heavily from previously successful IC designs, FPIX2, FSSR, SVX4, etc. The experiment will use a 106 ns beam clock. Each FPHX chip integrates and shapes (CR-RC) signals from 128 channels of mini-strips, digitizes and sparsifies the hit channels each beam crossing, and serially reads out the digitized data. The chip is designed only for positive charge (hole) collection from p-on-n detectors. The strips used by the experiment will have different lengths, resulting in a varying distribution of input capacitance across different chips. For the most part, activity is rare, but when there is an event, it is expected that there will be an average of 2.8% hit pixels per chip, with the possibility of much higher occupancy. Long latency cannot be tolerated, and it is therefore required that four hits will be read out within four beam cross-over periods of an event. A number of FPHX chips will be controlled on a single High Density Interconnect (HDI). Space on the HDI is limited, which is why the data from events must be serialized onto one or two pairs of LVDS digital lines per chip. In addition, the FPHX must be as “self-sufficient” as possible and provide its own internal bias voltages and currents with minimal external support circuitry. The user must be able to control internal parameters and biases, therefore a digital slow control interface is provided on each chip to enable programming.

The FPHX is a mixed-mode chip with two major and distinct sections, the front-end and the back-end (see Figure 9). The mostly analog front-end contains the 128 channels of integrators, shapers, and comparators, in addition to several programmable bias circuits and DACs that are used for setting internal parameters. The output of each front-end channel is simply an 8-bit digital word from 8 comparators (forming one hit discriminator output and seven thermometer-coded ADC outputs, which results in 3-bit magnitude information). Each comparator’s threshold is independently programmable, effectively allowing a custom non-linear ADC. The hit and ADC information serves as the input to the Core Logic section of the back-end, which processes the data for readout. Also part of the back-end is the Slow Controller, which accepts a serial data stream to program the chip after power-up.

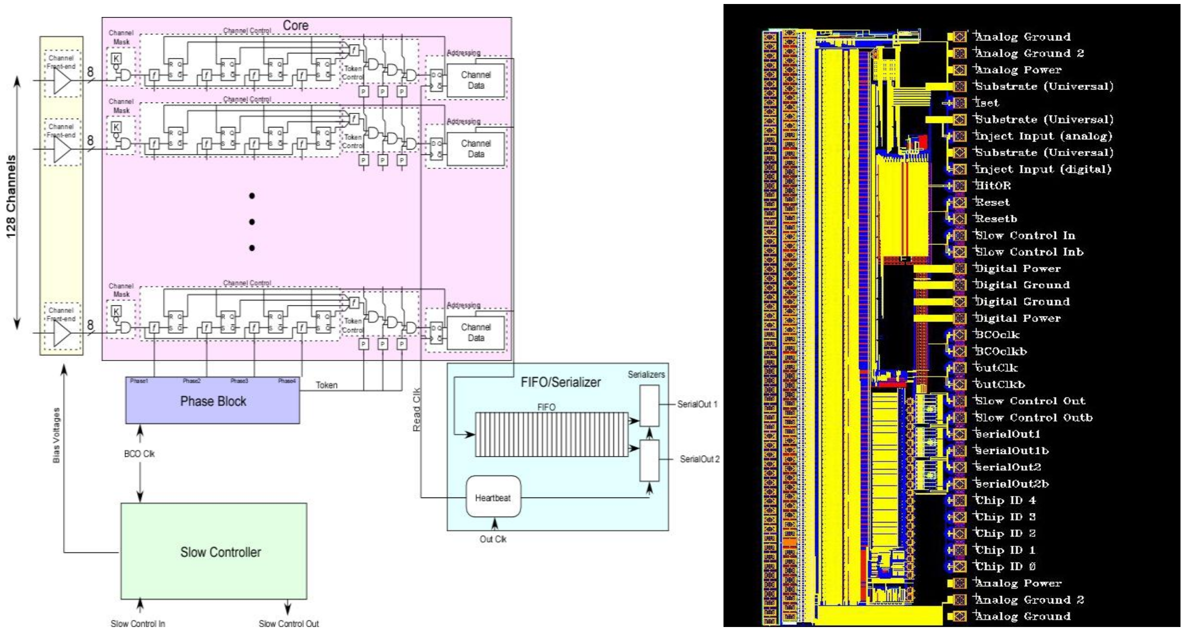

Figure 9. Left panel: Schematic design of the FPHX read-out chip. Right panel: Layout of FPHX chips with 128 strip input pads (left) and 32 input/output pads (right) for clock, slow control, calibration pulser, power and ground and signal output.

The overall architecture of the read-out chain is described in Figure 10. Each half-cage has 6 ROCs each connected to 16 sensor wedges. Each ROC is connected via optical fiber to a FEM, and 12 FEMs are grouped in a VME crate with a FEM Controller card. The ROC (Figure 11) will take the continuously streaming data (data-push) from 52 FPHX chips via flexible cables into an FPGA, strip the sync words from the data, combine the data of several chips, serialize it and send it out via fiber to the FEM and the Lvl-1 boards. The time to receive all of the data to pass to the Level 1 trigger is expected to be less than or equal to four beam clocks or 424 nsec. The location of the ROCs will be at the end of the silicon tracker enclosure in the “big wheel” area, as indicated in Figure 1. Twelve ROC boards will be required to service one endcap and these boards will hold a total of 48 FPGAs.

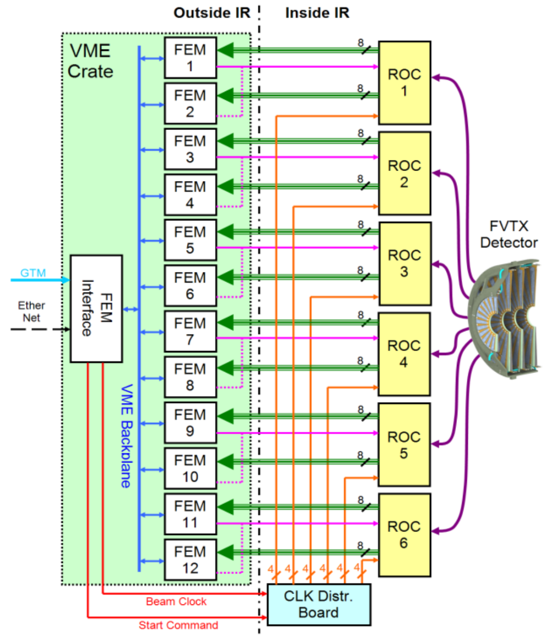

Figure 10. Schematic of the data-acquisition architecture for the FVTX detector. Each half-cage has 6 ROCs connected to 16 sensor wedges each. Each ROC is connected via optical fiber to a FEM, and 12 FEMs are grouped in a VME crate with a FEM Controller card.

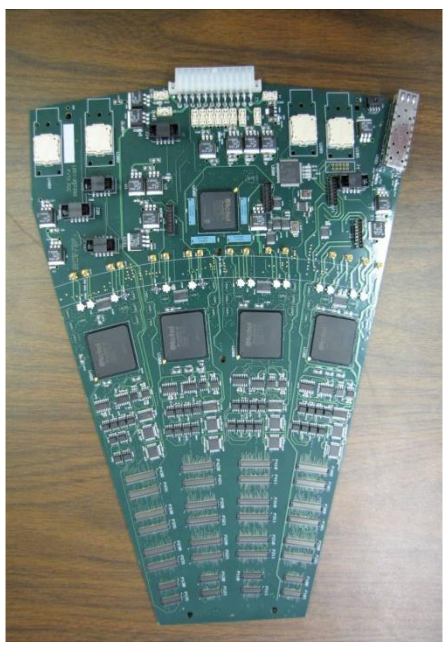

Figure 11. A production ROC board. Sets of two Hirose connectors at the bottom end are for connections to the sensor wedges. The ROC board also contains bias and power distribution, calibration distribution, clock and slow control distribution, and fiber optic outputs.

The FEM (Figure 12) will buffer the data for 64 beam clocks (emulating the 64 beam clock analog buffer of current PHENIX detectors), grab the data from the appropriate beam clock upon a Level-1 trigger and reformat the data before it is sent to the PHENIX Data Collection Modules (DCMs). There is a 64 FIFO array, with each FIFO storing the data from a particular beam counter. The FPHX data is routed to a FIFO, selected by the beam clock counter that is embedded in the data stream hits.

The hits from a particular beam crossing stay in the FIFO for not more than 64 clocks, otherwise they are marked as expired. This strategy solves the problem of relatively short beam clock counter wrap around. The FPGA then allows the data from the appropriate beam clock to be sent to the DCM when a LVL-1 trigger accept is received. Upon readout of the FIFO the hits from the expired beam crossing are not being outputted. The existing PHENIX DCMs can be used without modification.

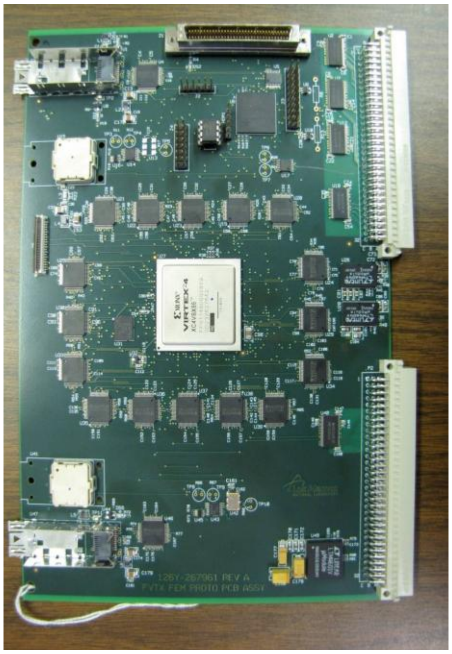

Figure 12. A production FEM board. It receives 32b parallel data from a single ROC channel over optical fiber at 125 MHz.

The current FEM channel design has been successfully implemented on an XC4VSX35 Vertex-4 XILINX FPGA and tested at design speed. The buffering block is capable of receiving 32 bit parallel data at up to 300 MHz and reliably sends the data to the output buffer at 300 MHz. Copying of the data from a particular FIFO to the output buffer should be done as fast as possible so that data from one beam crossing are fully emptied before data from another beam crossing arrives. The full design for FVTX readout is implemented on the largest VSX series FPGA XC4VSX55, which has a sufficient number of FIFO blocks to accommodate 4 FEM Channels on a single chip. The data from all 4 channels will be combined on the output in order to reduce the number of DCM channels in readout.

The entire production read-out electronics chain has been tested with a small number of wedges connected, and will soon be tested with a complete half-cage of wedges. We are currently awaiting the delivery of the production extension cables which will allow us to do this final pre-installation testing.

Figure 13. A production FEM interface board, which controls a VME Crate with 12 FEM boards.